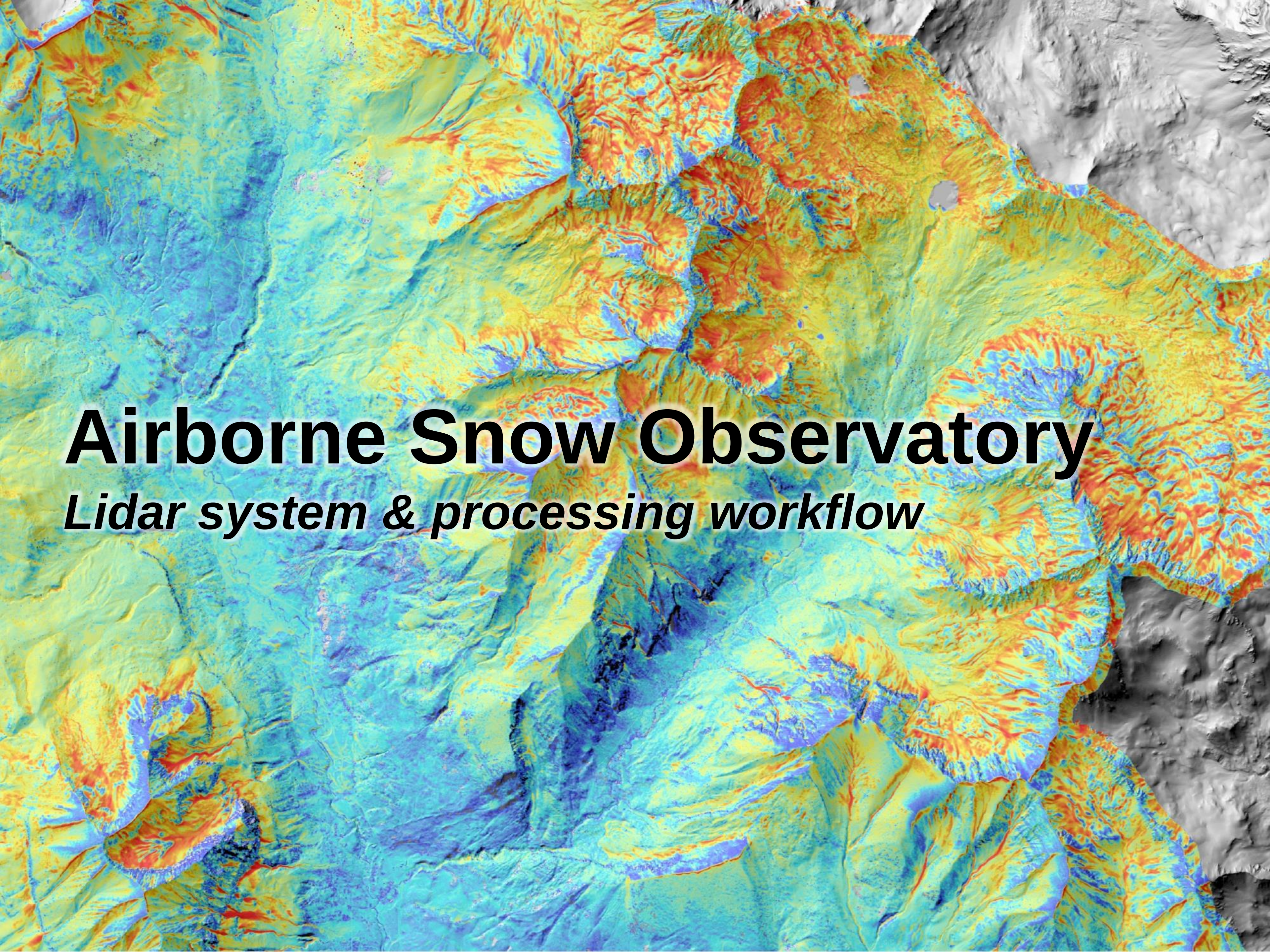


Airborne Snow Observatory

Lidar system & processing workflow

The NASA JPL Airborne Snow Observatory

Snow Water Equivalent

Riegl Q1560 ALS
800 kHz Pulse Rate
2 lasers with fore/aft pointing

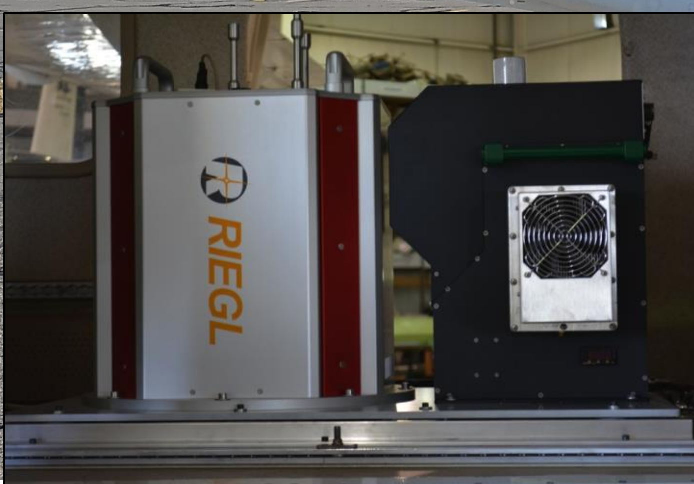
Snow Albedo

CASI-1500 Imaging Spectrometer
0.35-1.05 µm
2m spatial resolution from 4000m

ASO

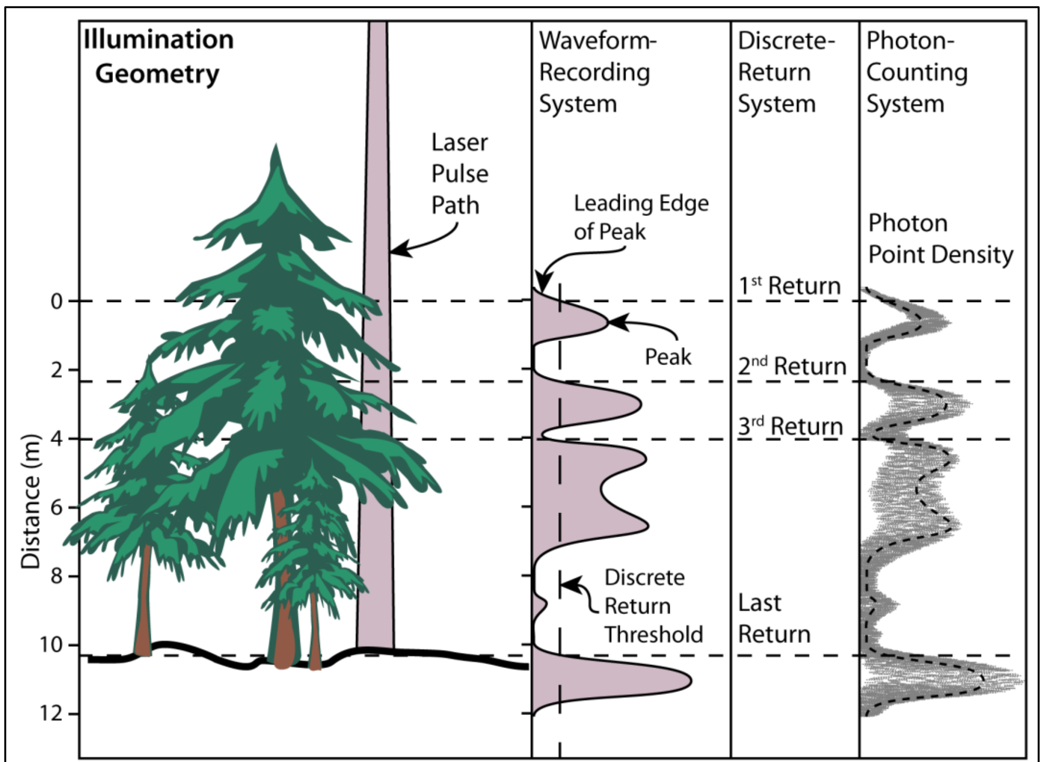
aso.jpl.nasa.gov

- Map surface elevations: snow-free & snow-on
- Difference gives snow depth
- SWE from assimilation of modeled density field constrained by observations
- SWE variation primarily due to depth
- Spectrometer maps albedo

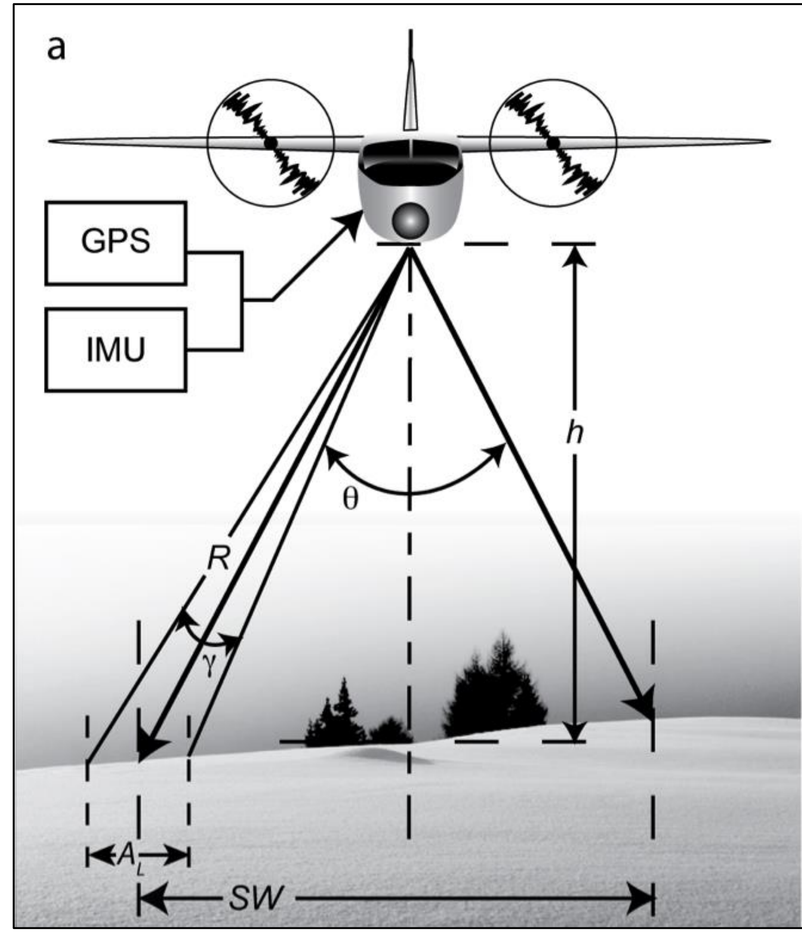


Lidar surface elevation mapping

- measures time-of-flight to target
- GPS/IMU system allows precise positioning of each laser shot
- product: high-resolution surface elevation map



(Deems et al., 2013)

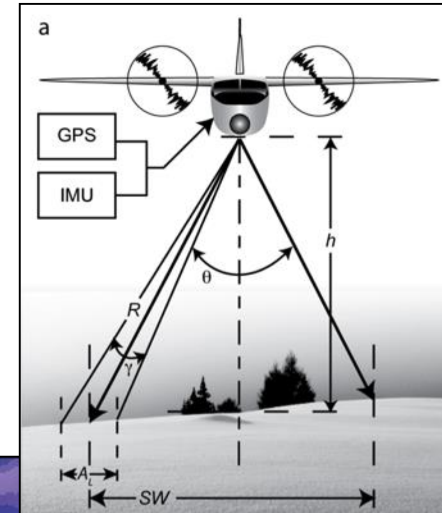


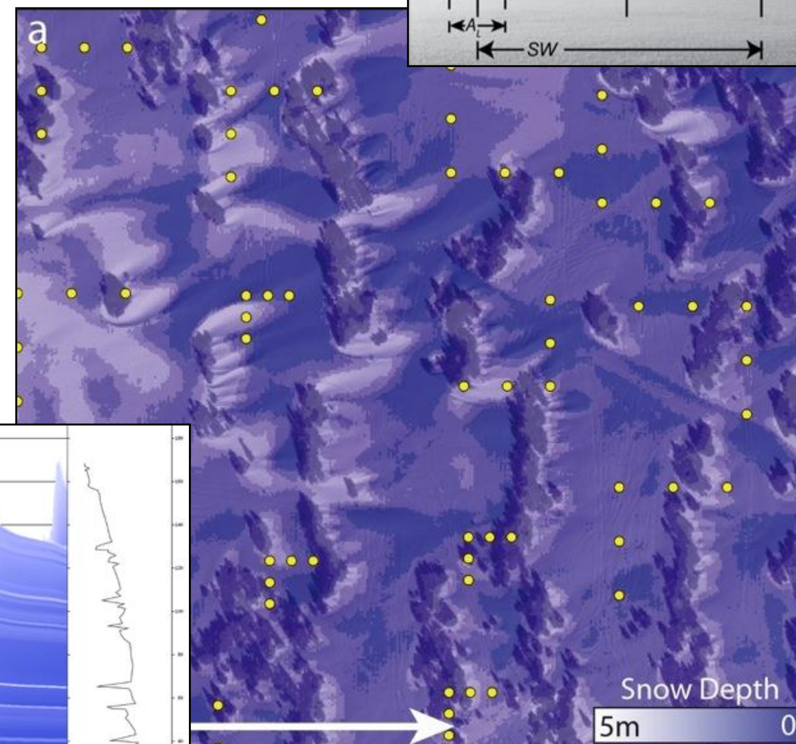
(Deems et al., 2013)

- beam spread allows sub-canopy mapping in forested areas

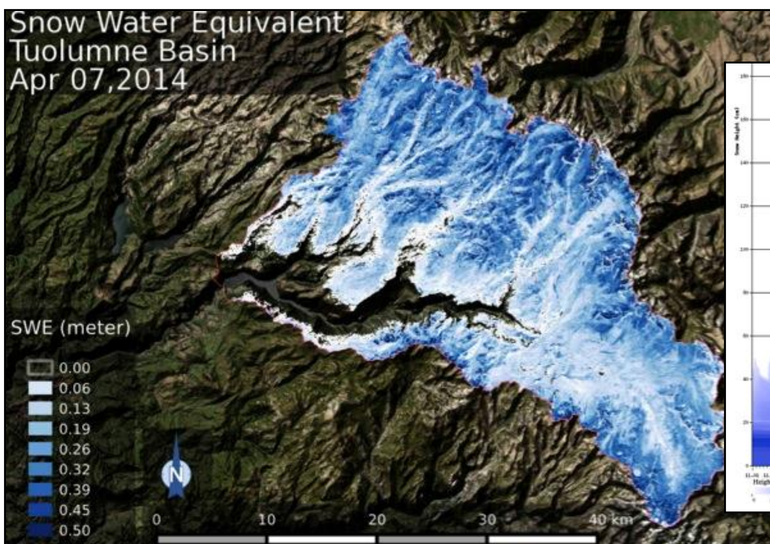
Snow depth & SWE from lidar

- majority of SWE spatial variability due to snow depth
- depth measured by differential elevation mapping
  - collect snow-free & snow-covered data sets
  - classify & remove vegetation points
  - subtract snow-free from snow-covered
- apply obs/modeled density
  - SWE = depth * density
  - SNOTEL/manual obs + snow model to estimate density

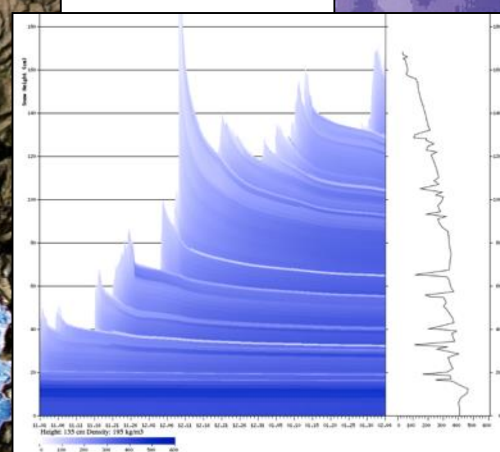




lidar-derived snow depth, Colorado (Deems et al., 2013)



ASO lidar-derived SWE



SNOWPACK courtesy CAIC

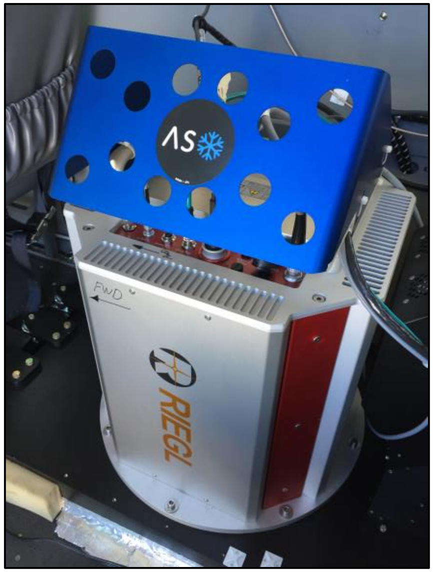
The NEW

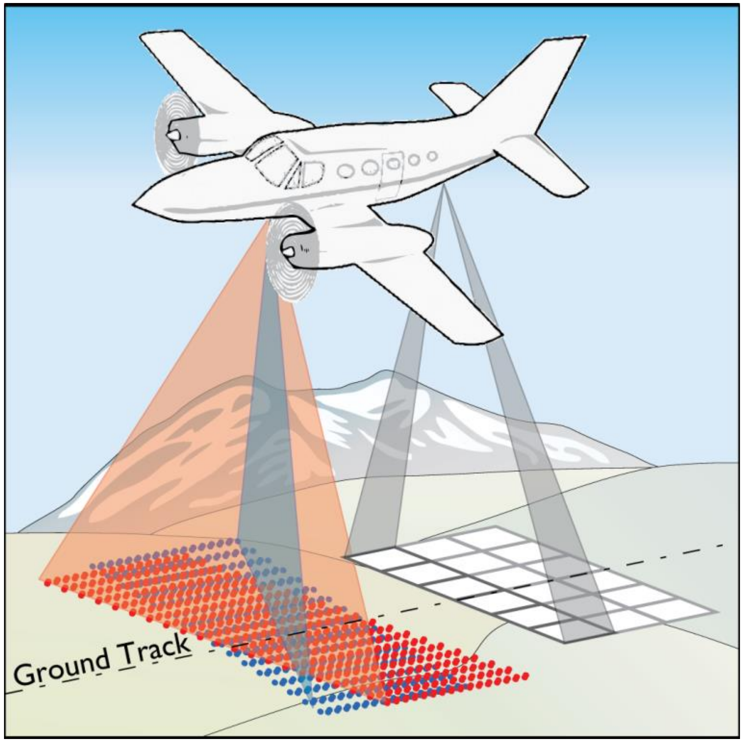
RIEGL LMS-Q1560

fully integrated dual channel
airborne mapping system

System integration & configuration advantages

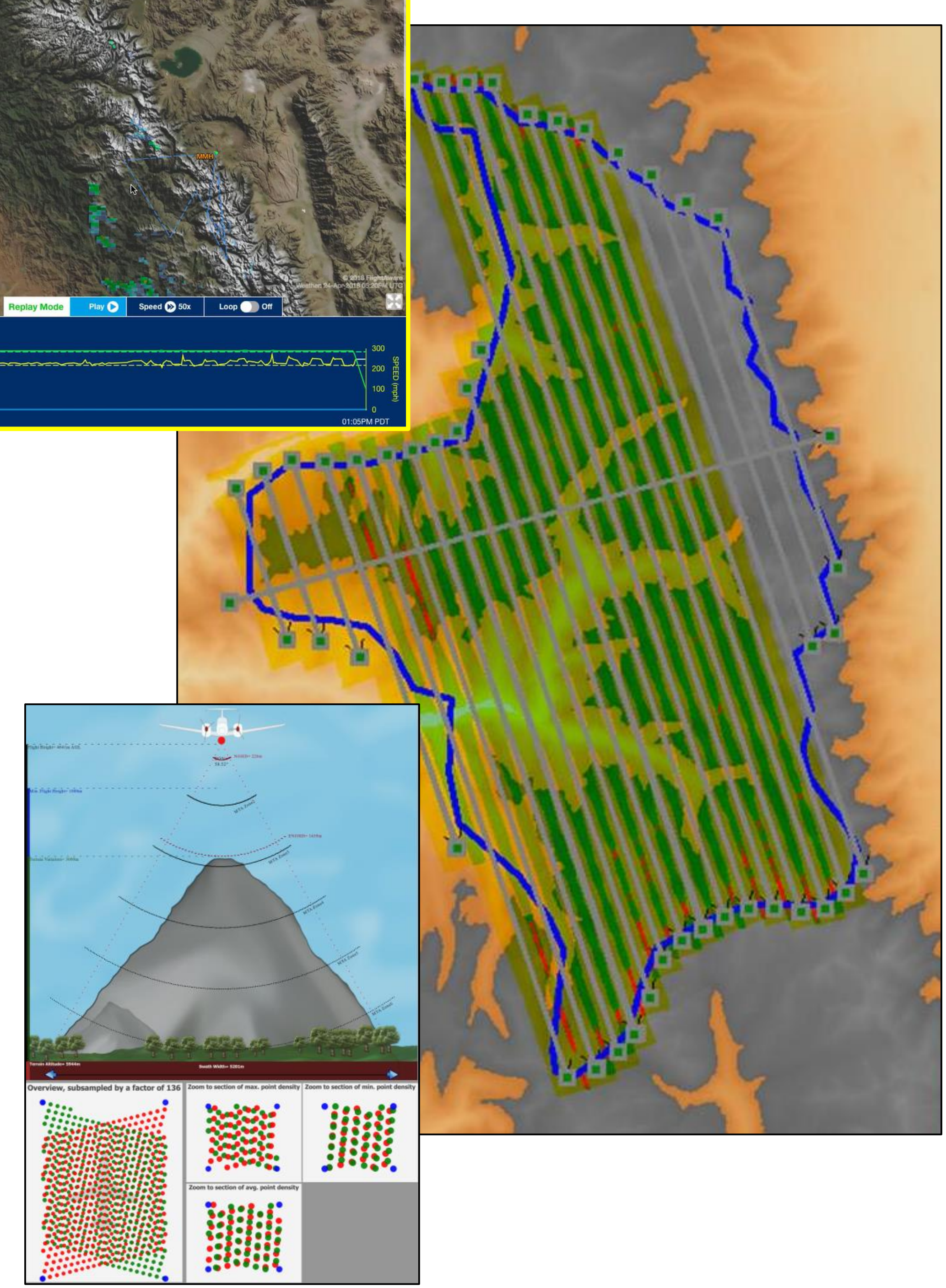
- Twin lasers double point density
- Range consistently exceeds spec (5000m+ AGL)
- Fore/aft pointing enhances coverage & geometry in steep terrain
- Full waveform processing improves subcanopy surface detection
- Integrated RGB camera for improved quality control, visualization, & snow detection
- Payload integration mount ensures consistent instrument alignment
- Integrated Applanix 610 IMU reduces boresight drift
- Trimble RTX service allows faster trajectory generation & speeds workflow
- Flight planning for CASI FoV (34°) allows large Q1560 overlap (60°) & greater shot density





itres

RIEGL®
LASER MEASUREMENT SYSTEMS



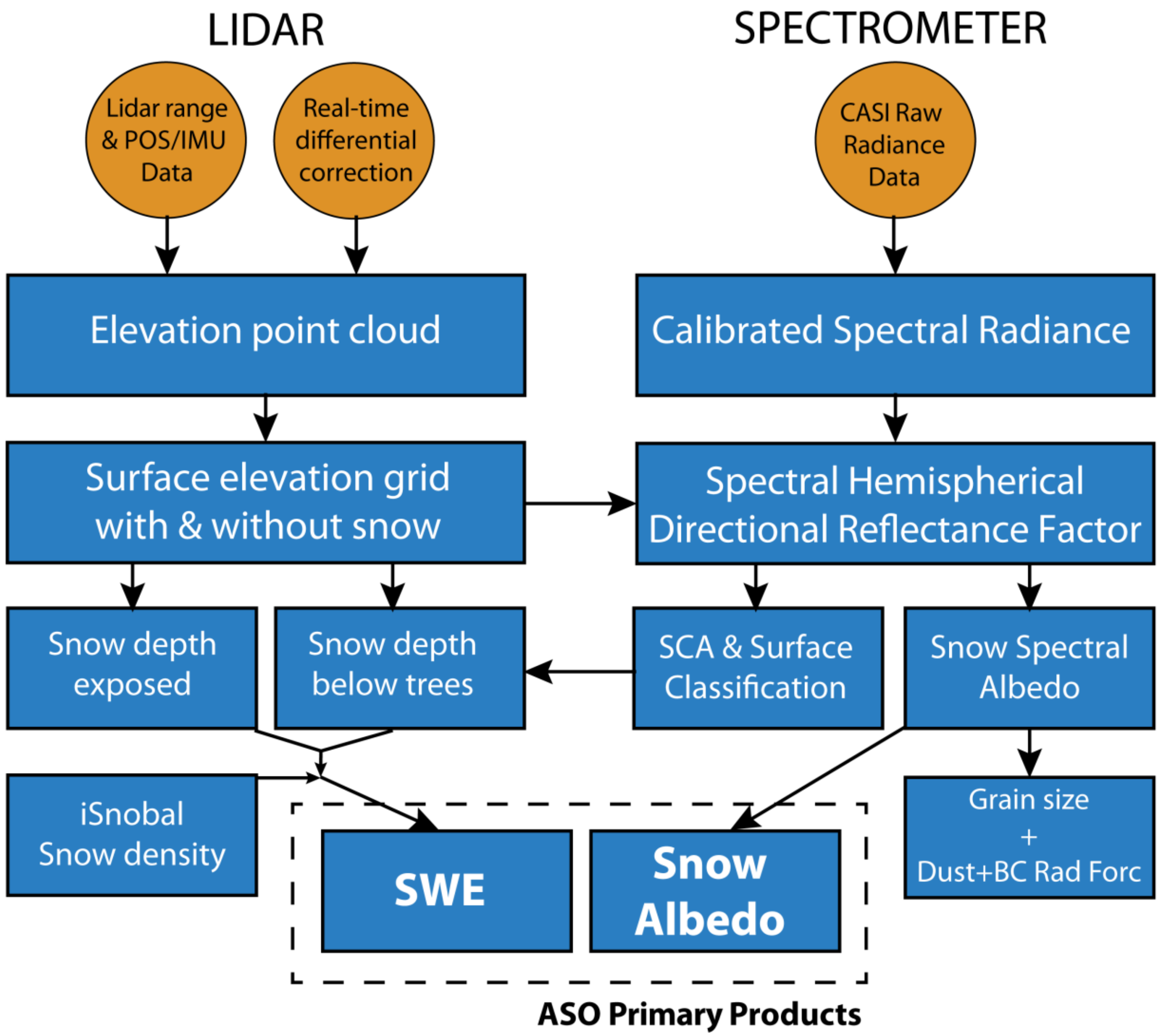
flight planning & survey parameters

- flight planning optimized for:
  - efficient areal coverage
  - CASI mapping
    - 20% swath overlap
    - N/S (± 20°) line orientation
  - change detection & volume calculation
- different from conventional topographic surveys:
  - not targeting a specific or constant point density
    - lower point densities tolerated in lower elevation areas
  - relative registration is priority

ASO Compute System

operational products

- 24-hour turnaround for established basins
- maps of:
  - snow depth
  - SWE
    (using observed + modeled densities)
  - broadband albedo
- aggregated to operational model resolution



Lidar processing

Trimble PosPac

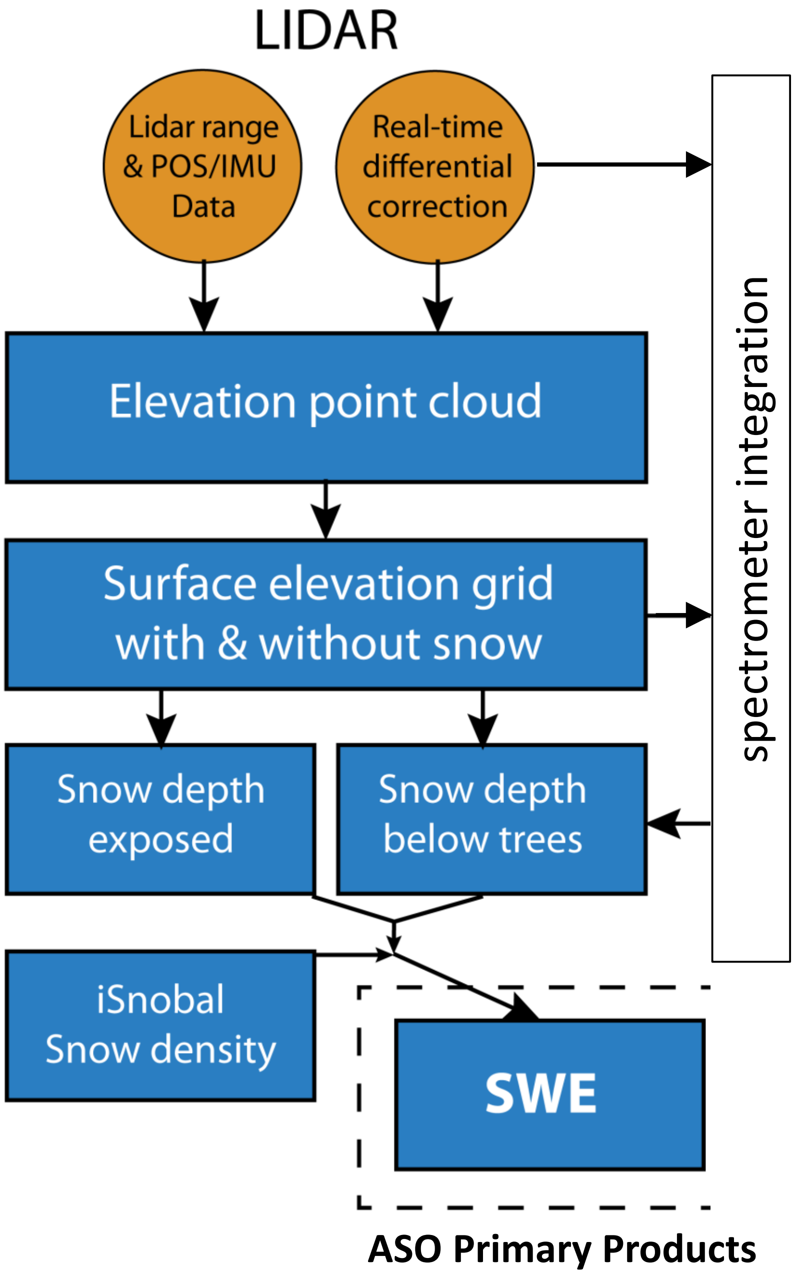
- convert real-time corrected POS/AV feed to SBET format (*PosPac*)

Riegl RiPROCESS

- extract point cloud from raw waveforms (*RiANALYZE*)
- georeference point cloud (*RiWORLD*)
- export point cloud to LAS 1.2 in UTM projection (*RiWORLD*)

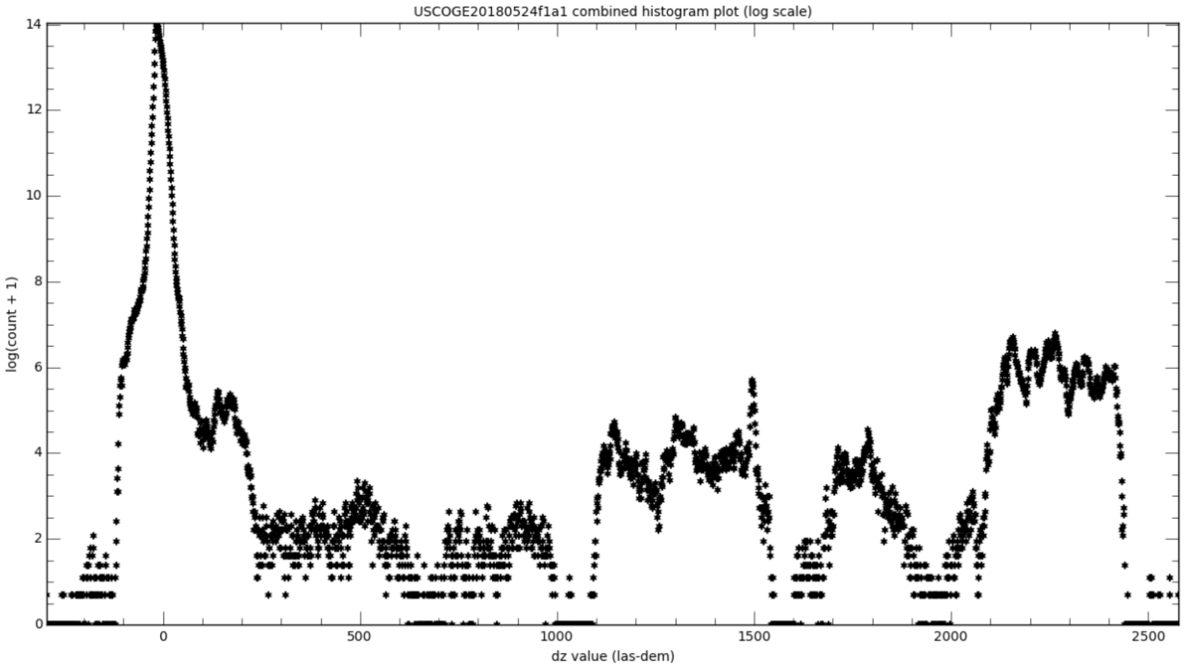
Custom IDL solution

- filter isolated points
- export First Surface Return (FSR) DSM for CASI raytracing
- classify point cloud into ground/not-ground with MCC algorithm
- export bare earth DEM/DSM



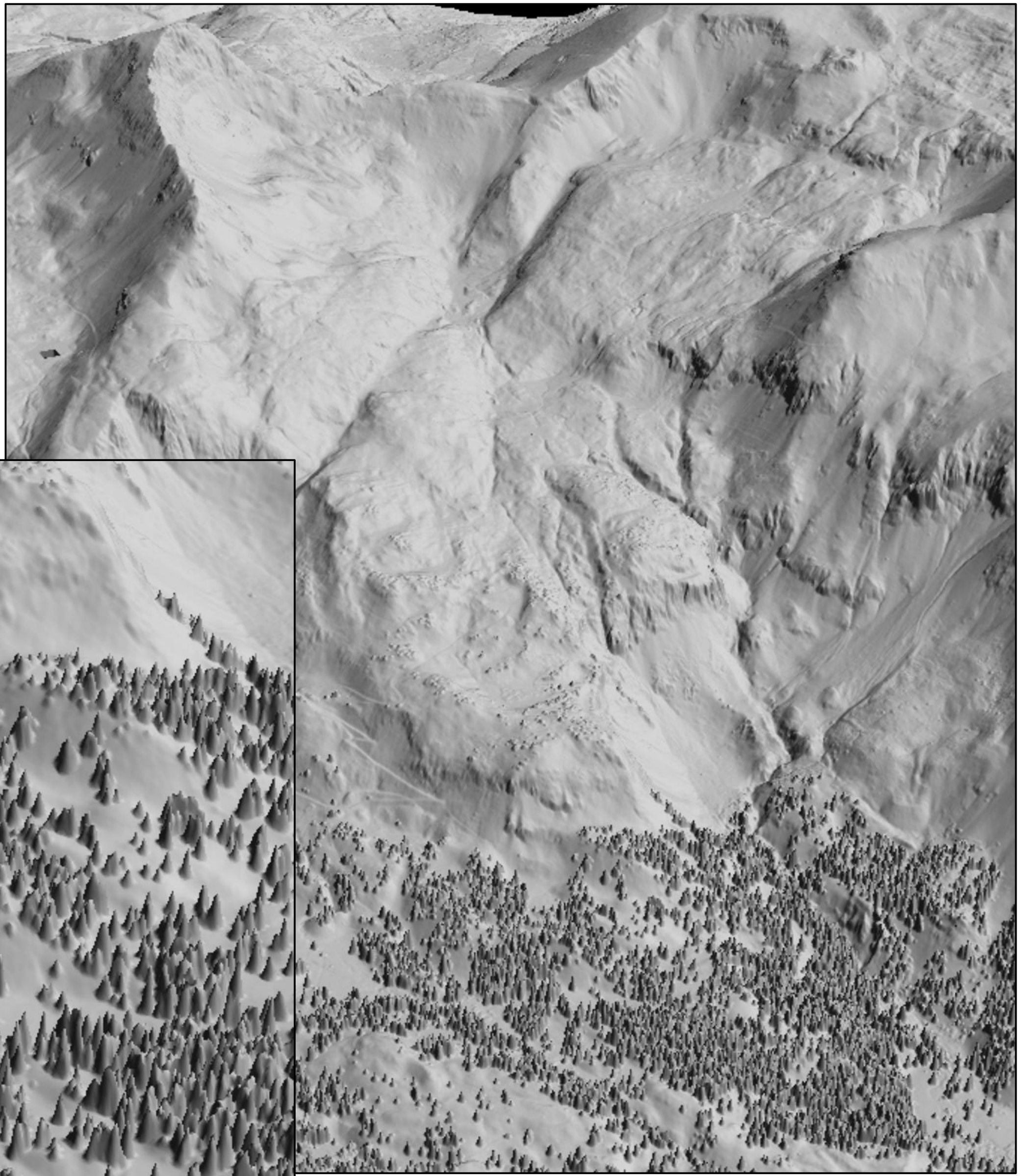
Isolated point filtering

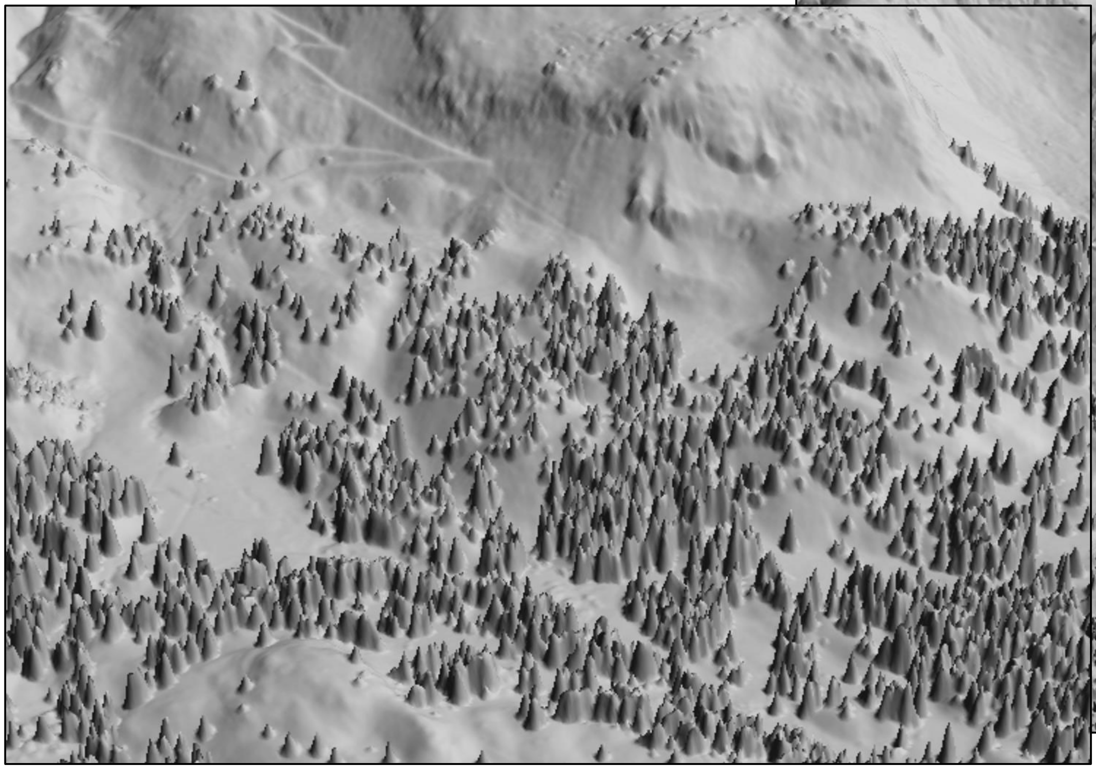
- In-air points are treated as noise
  - Clouds
  - Water vapor
  - Particulates
- Histogram of elevation differences from reference DEM is examined
- Points with elevation difference > threshold are removed



First Return Surface (FSR) Gridding

- 3m elevation grid created from 1st returns
- Spectrometer ray-traced to this surface for orthorectification

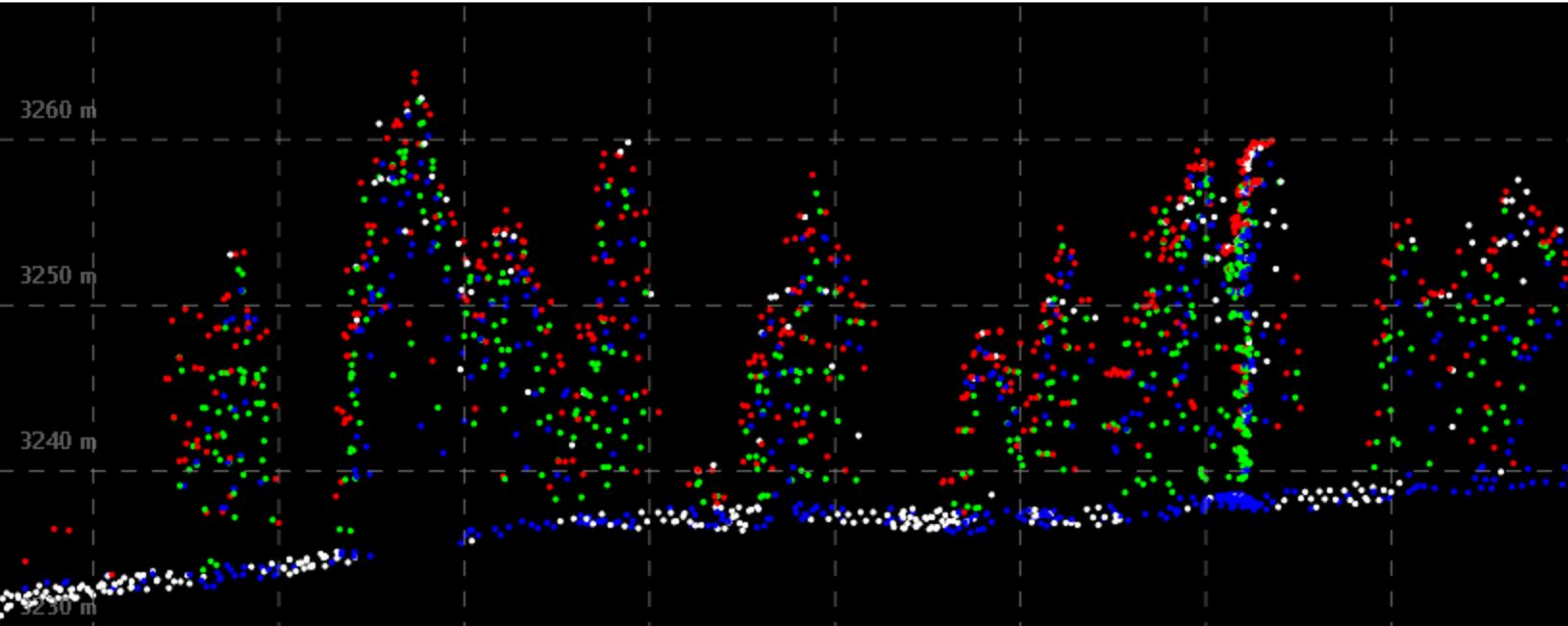




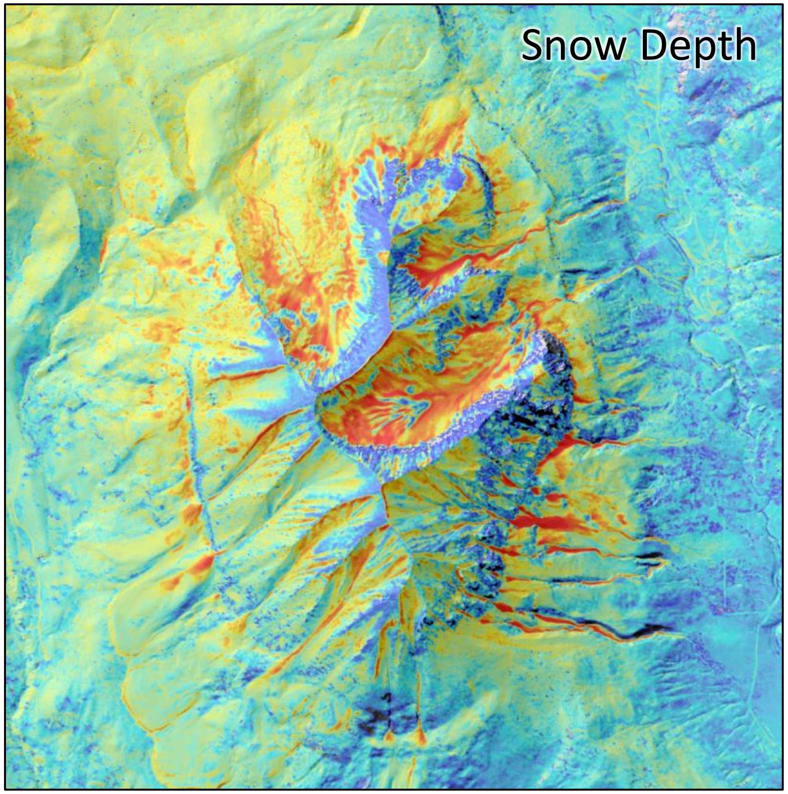
Point-cloud difference DEM generation

PCDTM: Bare-earth DEM & “bare-snow” DSM are generated from the unclassified point cloud

- Calculate mean of lowest quartile in each 3x3m grid cell
  - More efficient than classification & gridding of ground points
  - More transferrable than customizing classifier parameters for each site
- Takes advantage of normal error distributions



Snow depth calculation

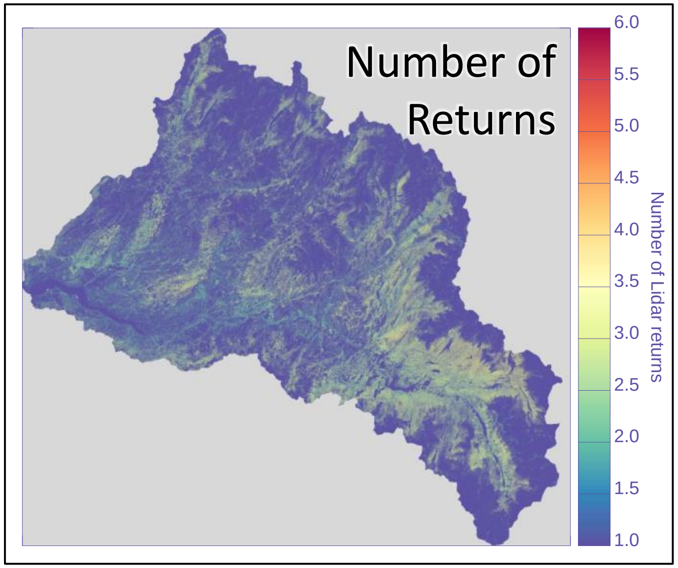


snow-on DSM:

- forest areas delineated by combination of CASI land cover classification & areas with > 1 lidar return per pulse
- hybrid DSM created from FSR grid (in open areas) & PCDTM grid (in forest)

snow depth calculation:

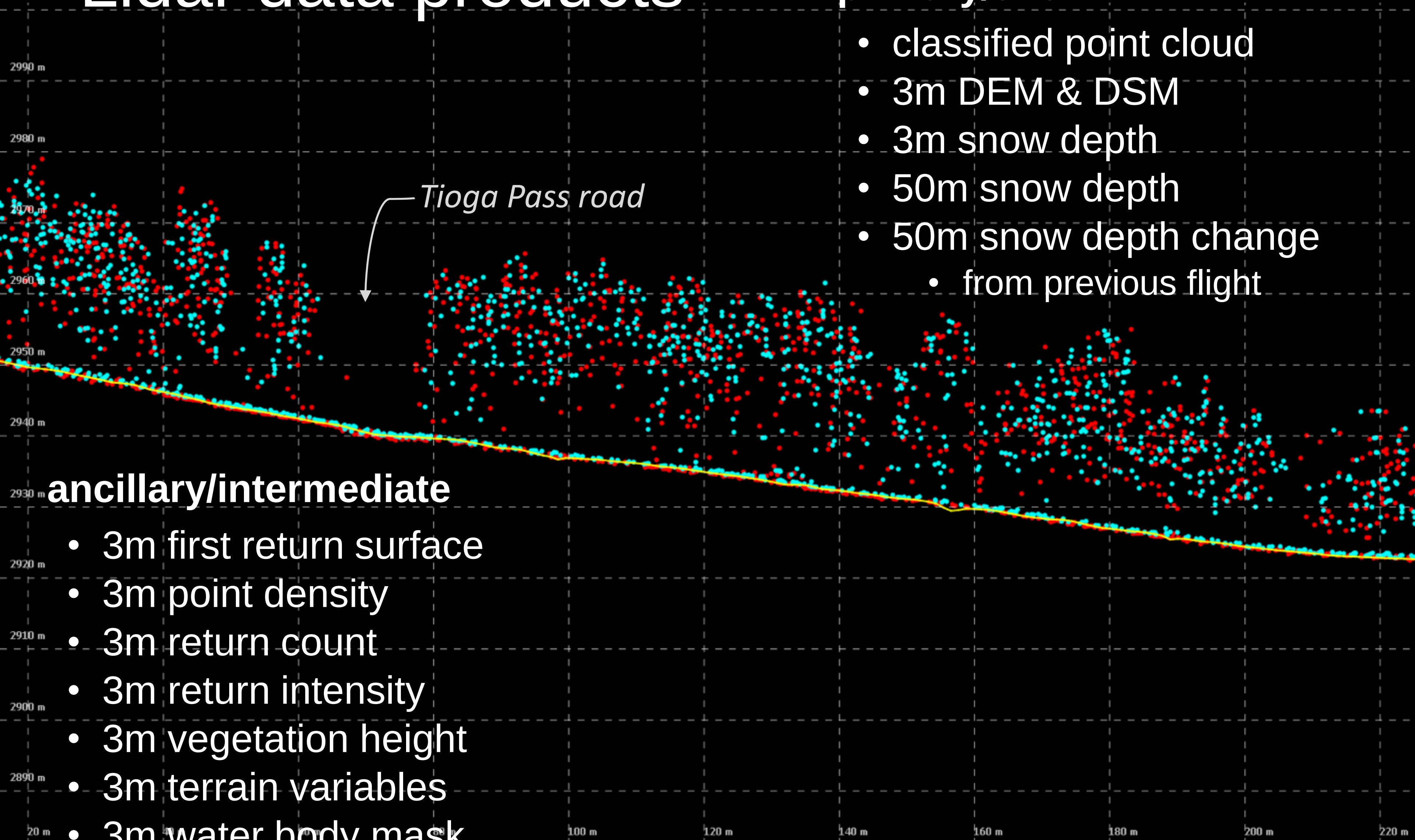
- mask for SCA:
  - CASI snow class where illumination is good
  - lidar return intensity where illumination is poor
- subtract snow-off DEM from hybrid snow-on DSM
  - only where snow exists
  - Snow-on grid bias-adjusted to ensure zeros where no snow



Lidar data products

primary/snow

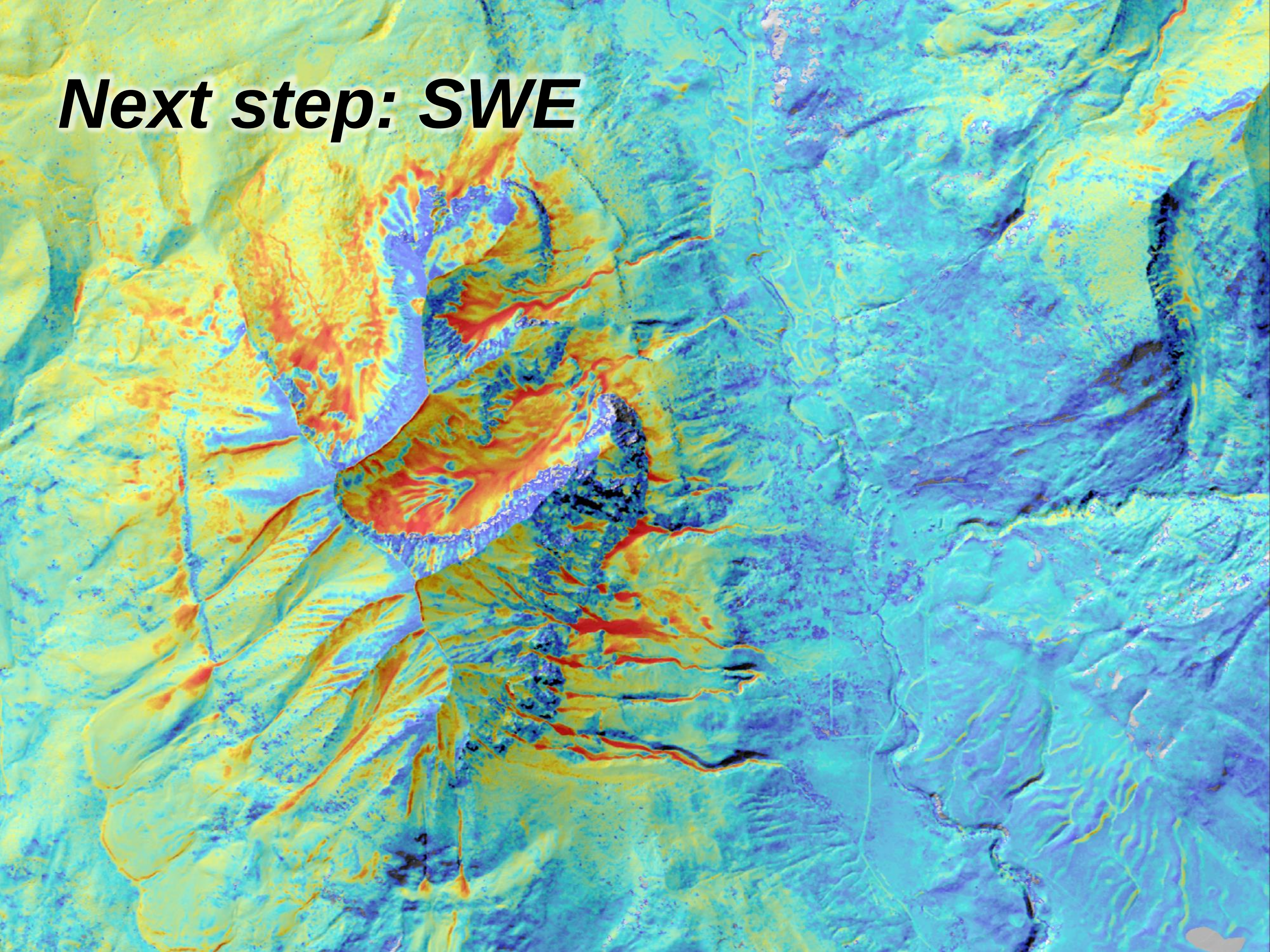
- classified point cloud
- 3m DEM & DSM
- 3m snow depth
- 50m snow depth
- 50m snow depth change
  - from previous flight



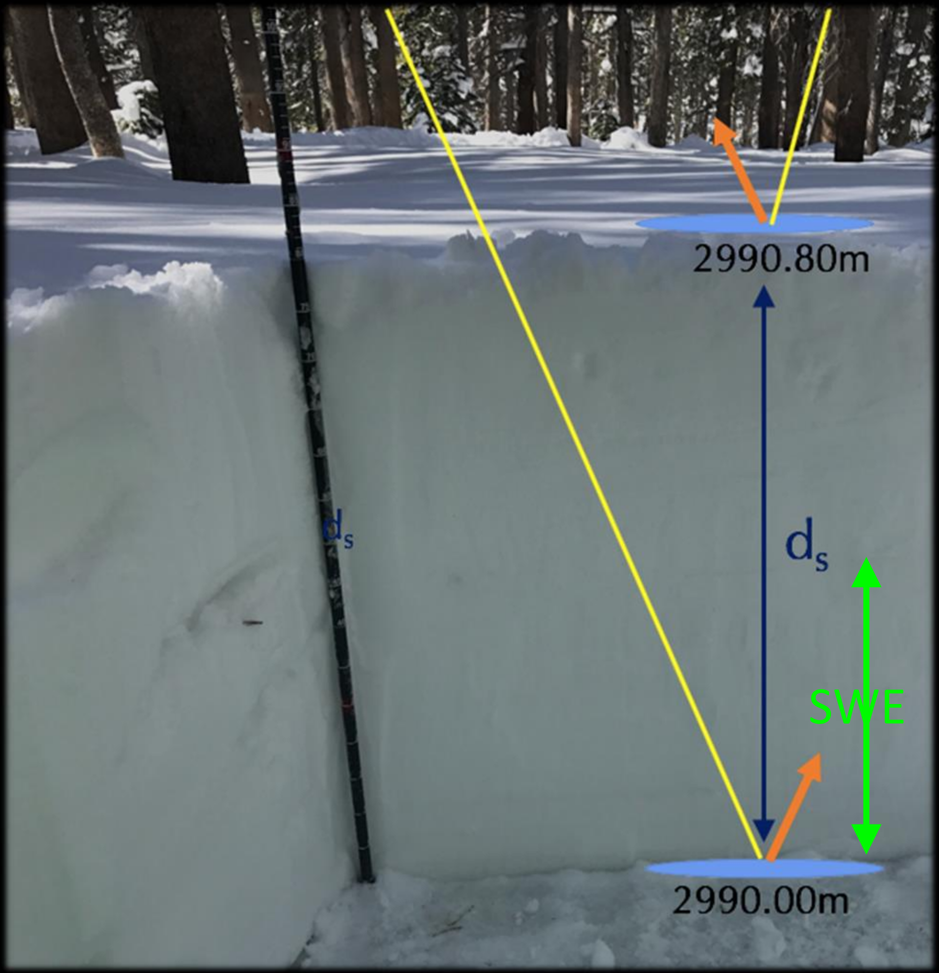
ancillary/intermediate

- 3m first return surface
- 3m point density
- 3m return count
- 3m return intensity
- 3m vegetation height
- 3m terrain variables
- 3m water body mask
- 3m surface roughness

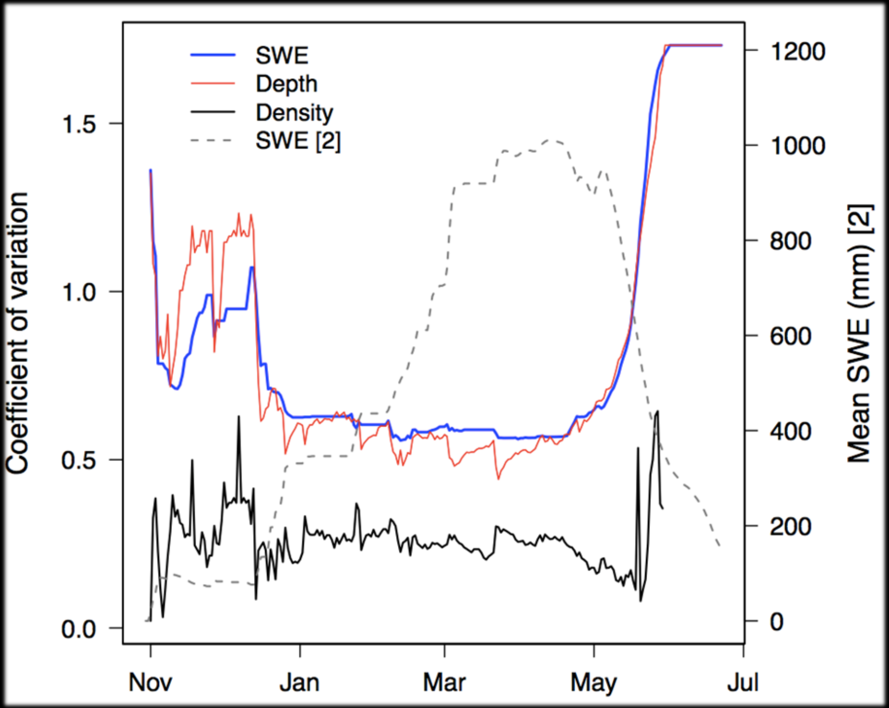
Next step: SWE



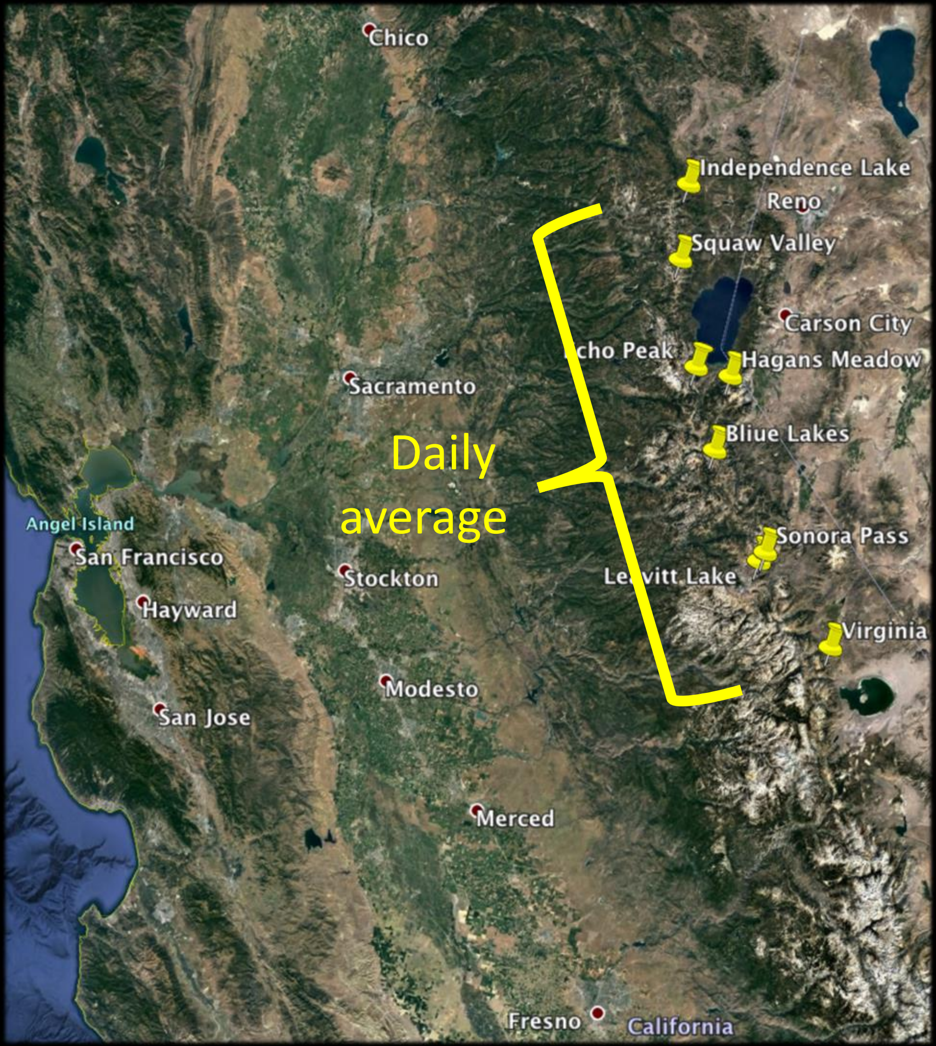
Snow depth to SWE



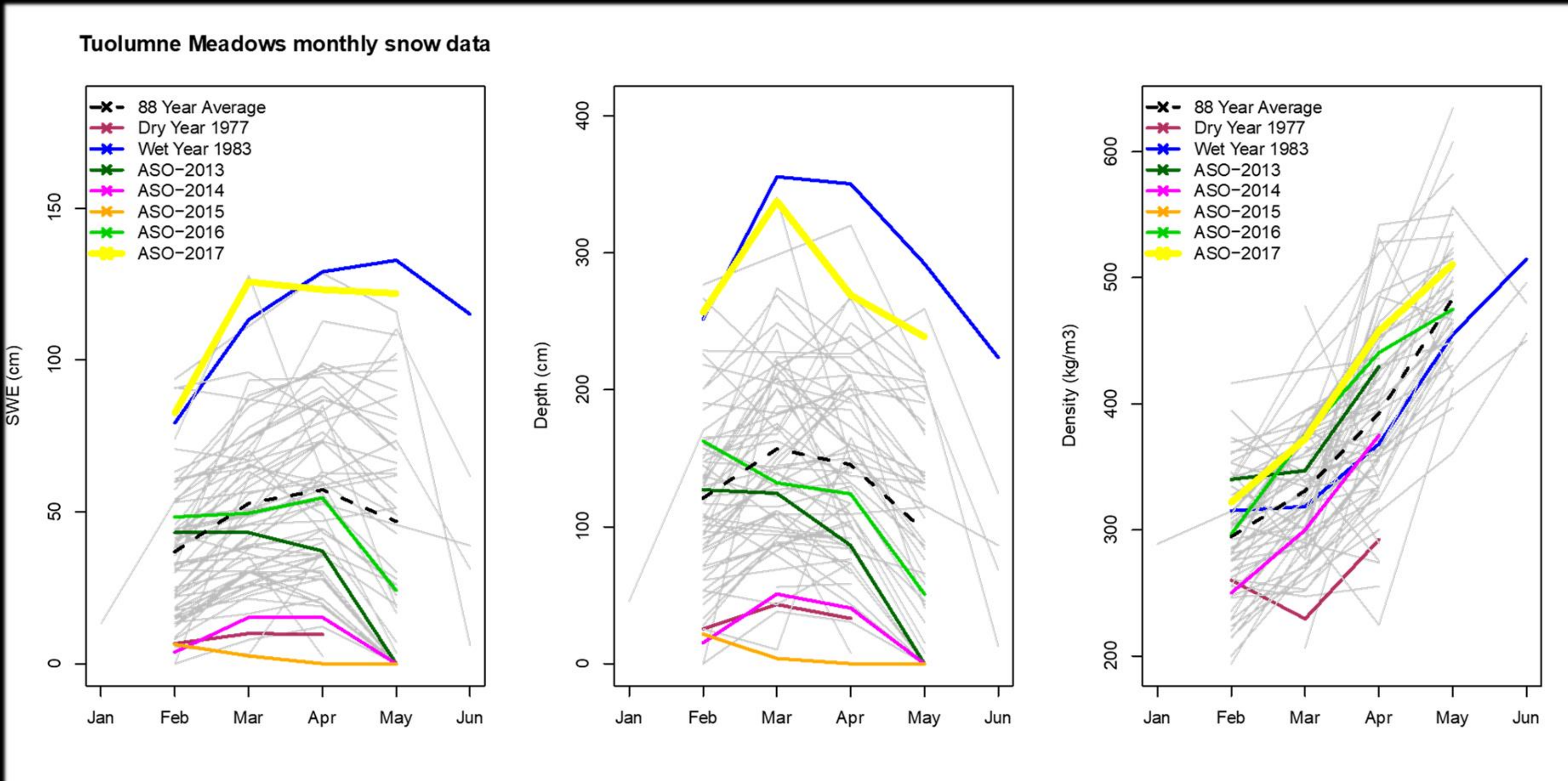
SWE variability driven by depth variability



Painter et al., 2016

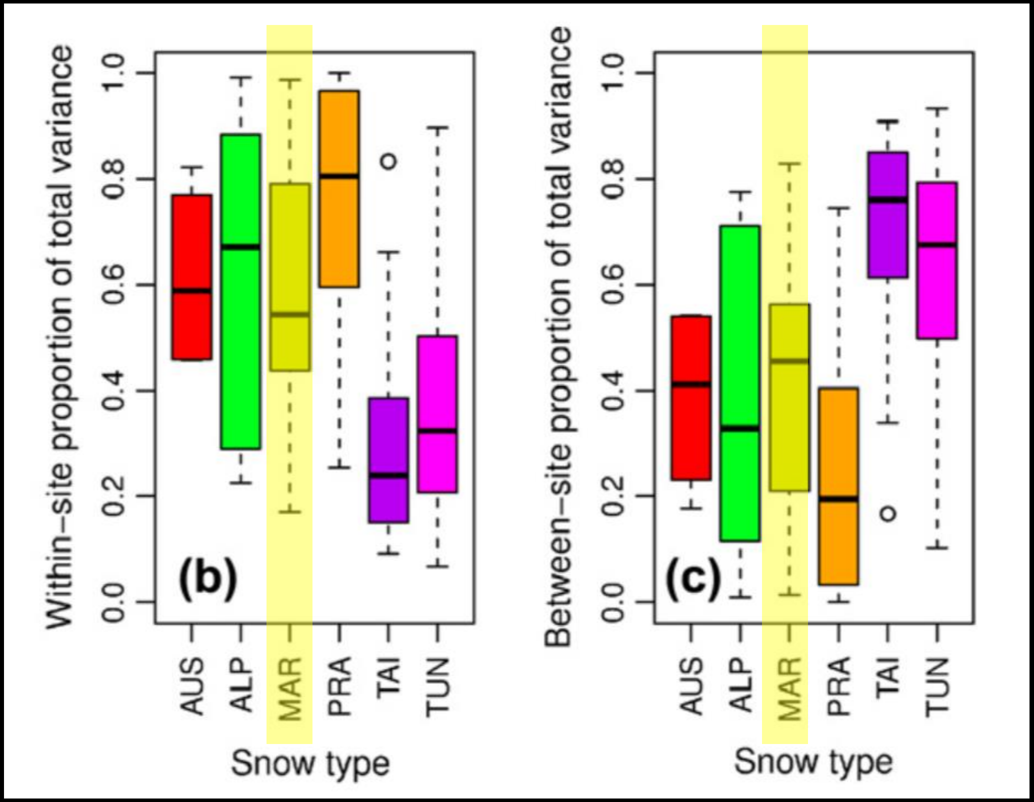


Snow density interannual variability



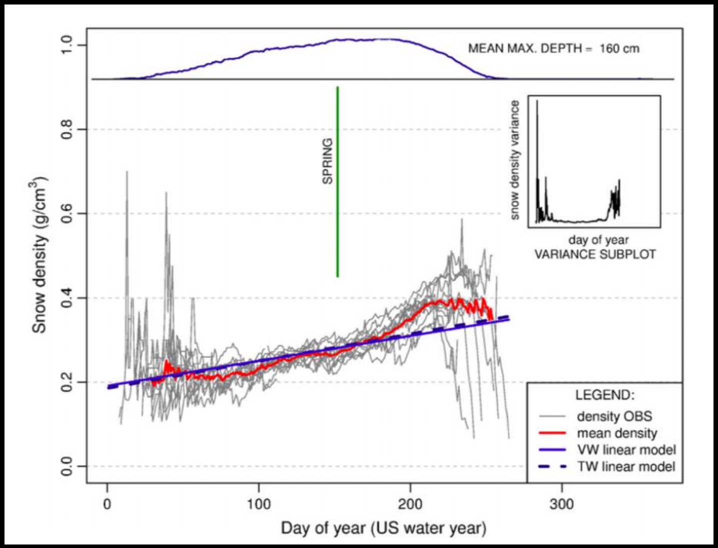
Ranking modes of snow density variability

#2. Interannual 45-80%   #3. Spatial 20-55%



Bormann et al., 2013

#1. Seasonal progression

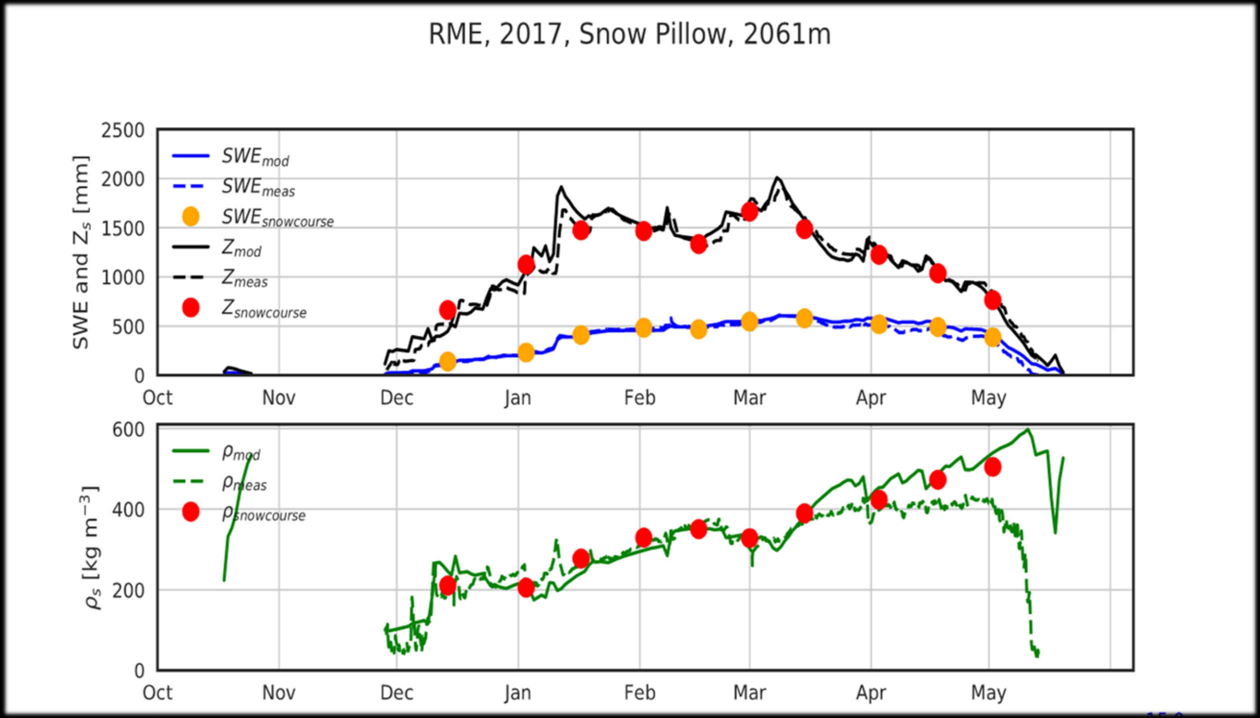


These processes must be captured for conversion of ASO snow depth to SWE

iSnobal model tracks snow density

ARS developed new algorithm for iSnobal
Physically-based and includes:

- Compaction (event based)
- Metamorphisms
- Liquid water additions



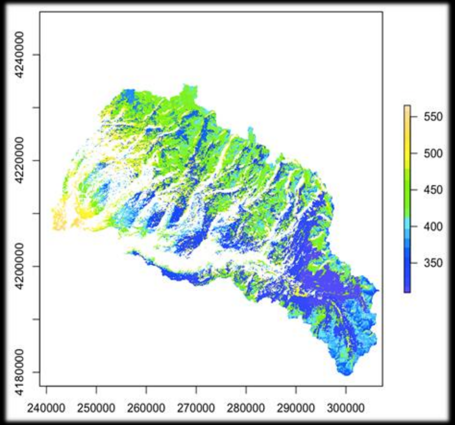
Marks et al. (in review)

ASO Operational snow density procedure

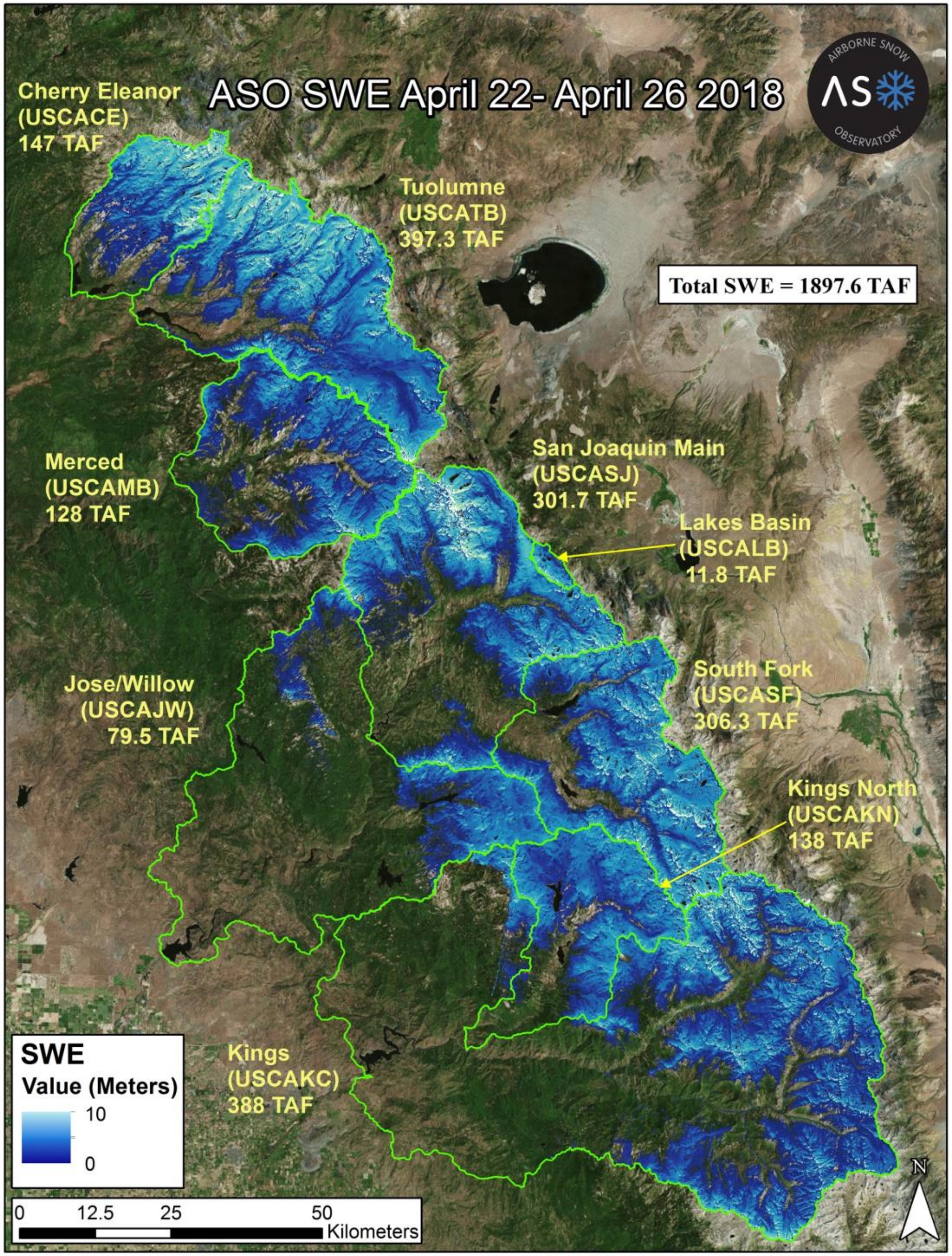
1. Retrieve modeled snow density maps from ARS

2. Evaluate with in-situ measurements
   - Snow pillow, snow course, snow pit
   - Recent weather, avalanche info.

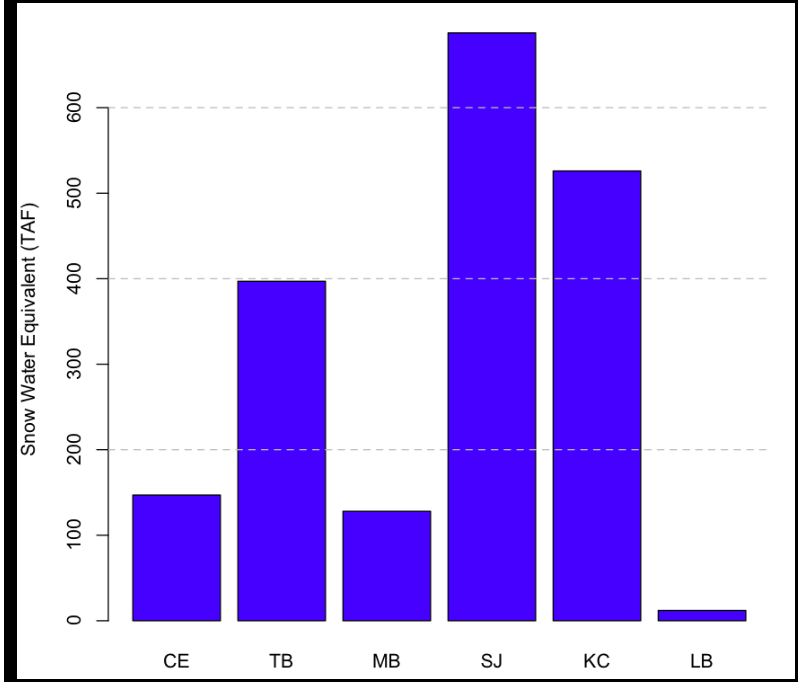
3. Apply adjustment if required
   - New snow density algorithm
   - Smaller changes



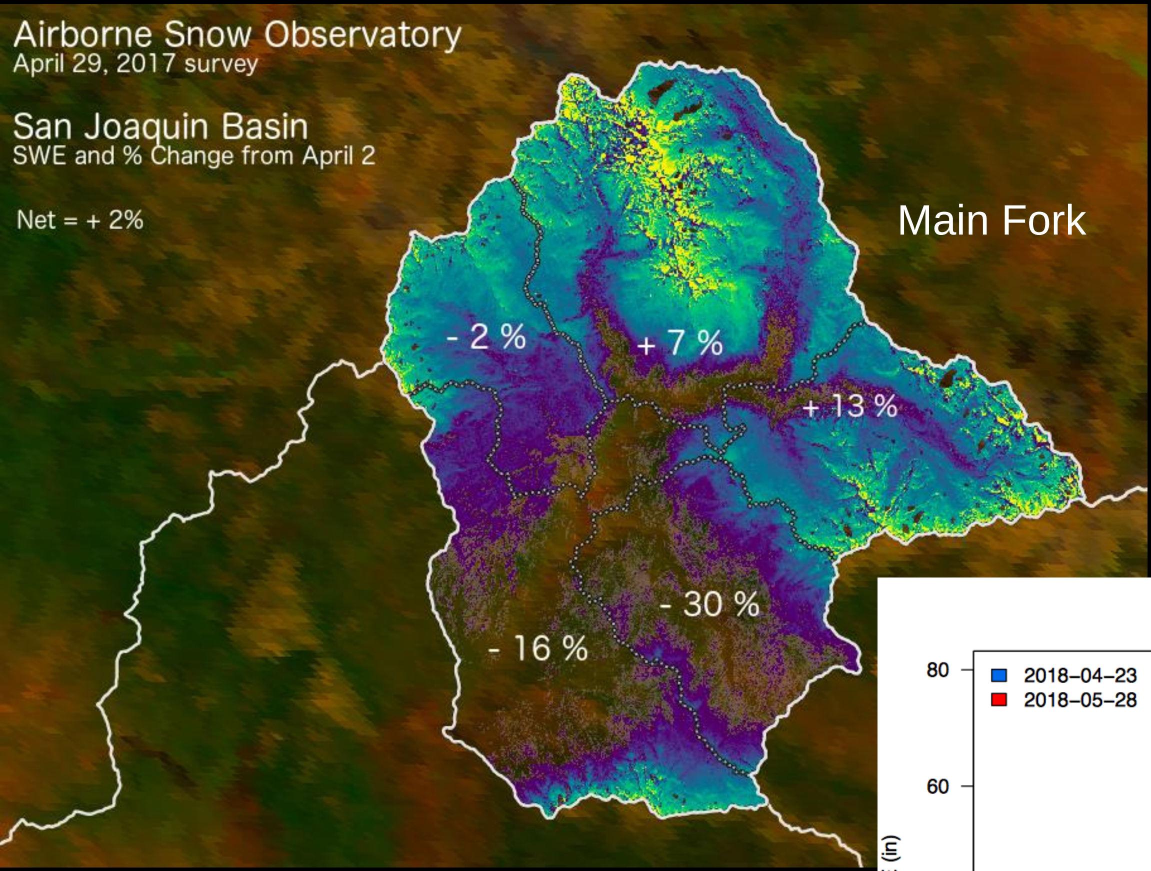
4. Snow depth x density = SWE (per pixel)



SWE at 50m resolution

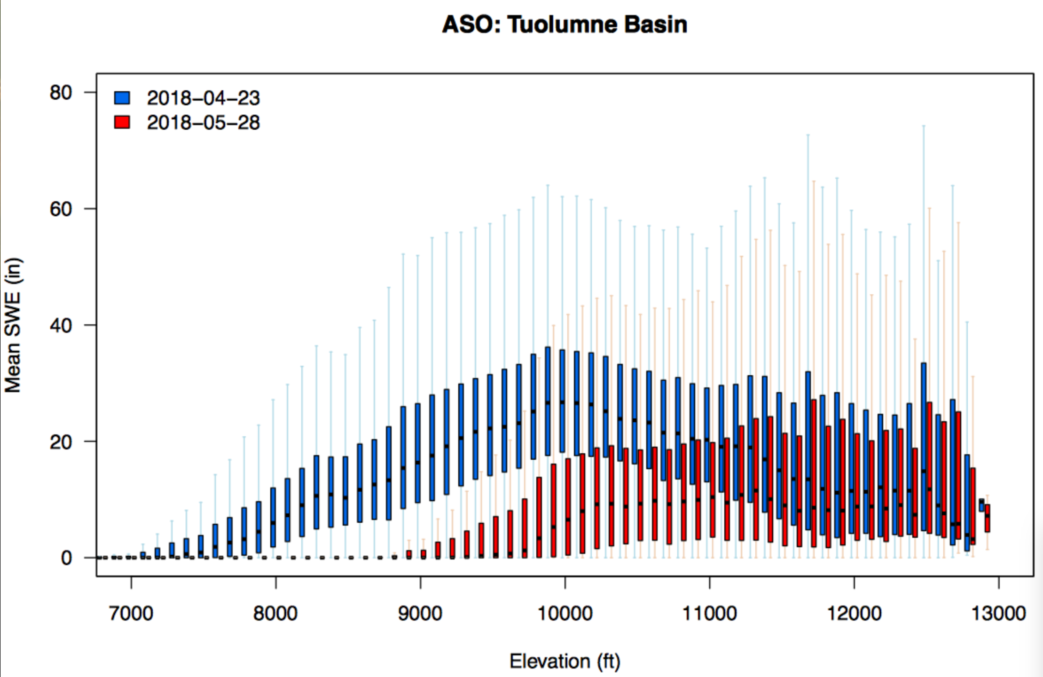


SWE Data Distillations



Main Fork

Elevation band SWE

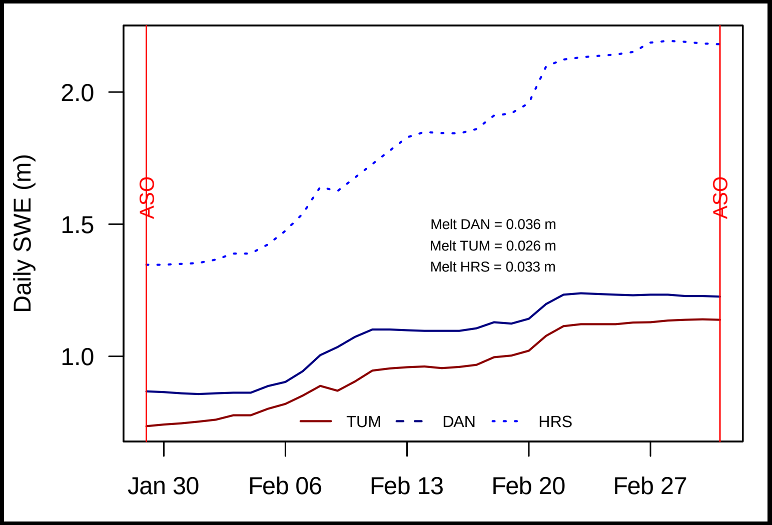


Subbasin SWE & change quantification

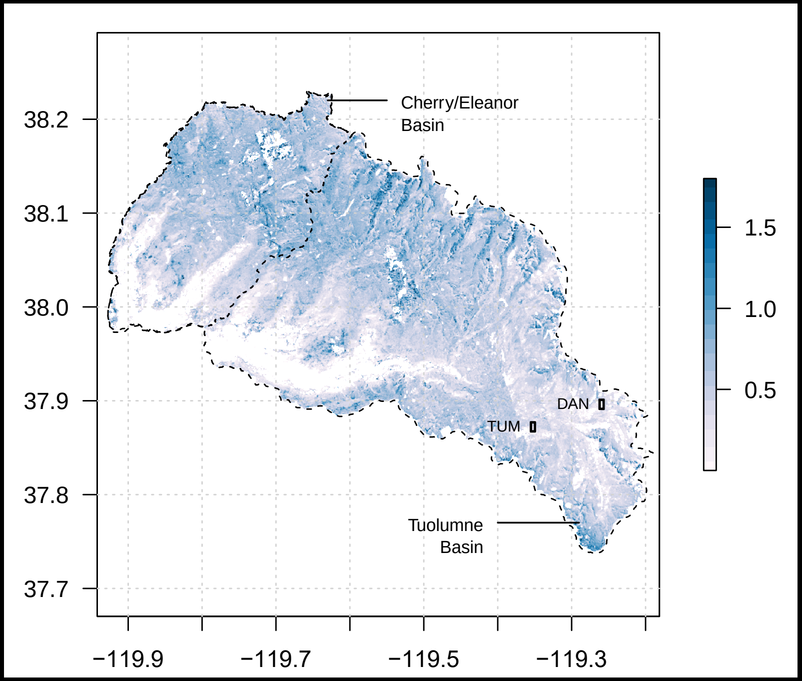
ASO vision in hard to reach places

- Above in-situ elevations (inaccessible terrain)
- After snow pillows melt out
- Post-snowfall event (including AR's)

SWE Accumulation map



Feb 2017 Tuolumne



Behrangi et al., (2018)

ASO 2018 season

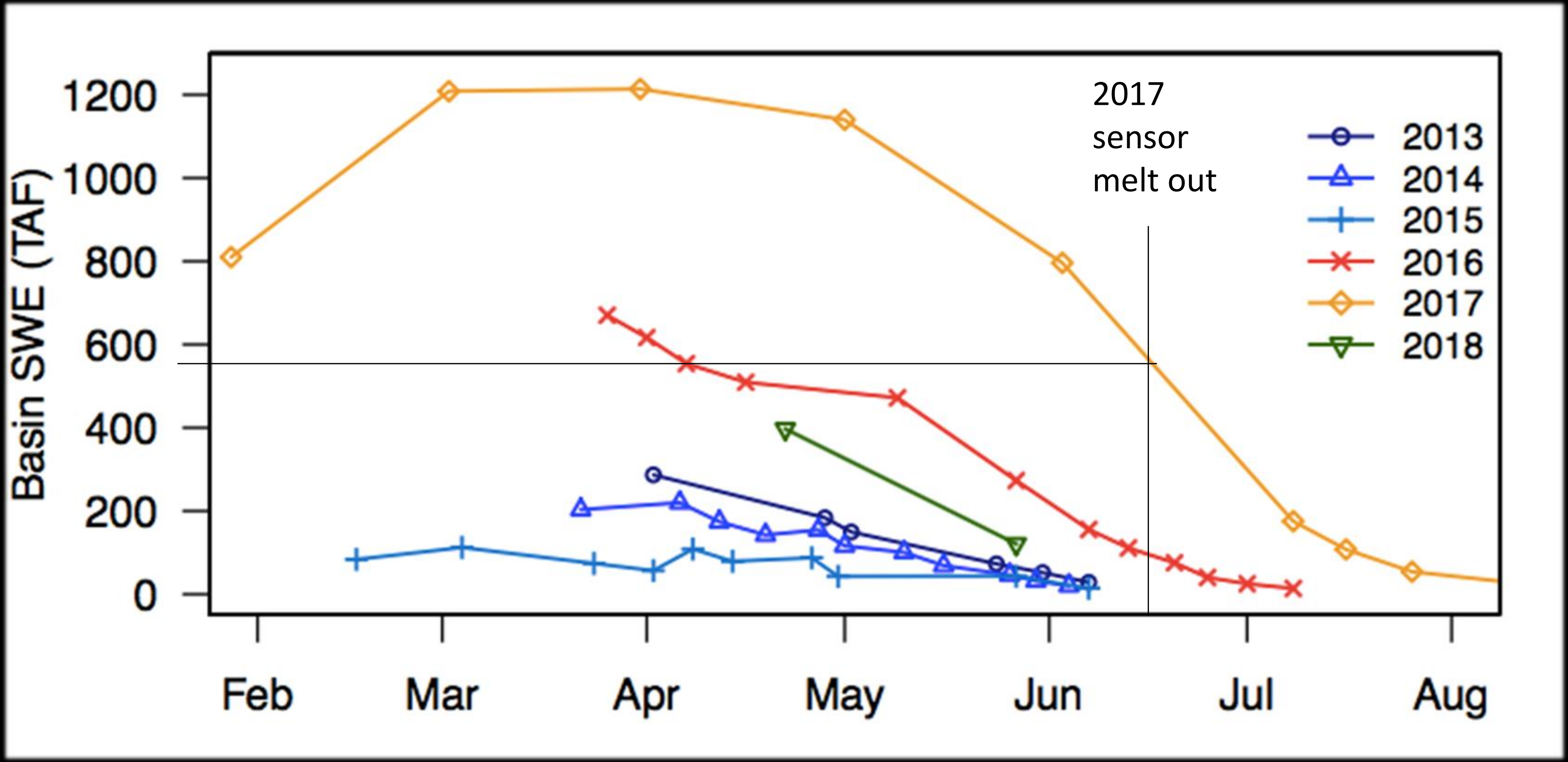
Building on a 6 year legacy in the Tuolumne

- 23 operational surveys
    - San Joaquin x 3
    - Tuolumne/Cherry/Eleanor x 2
    - Lakes Basin x 3
    - Kings x 1
    - Merced x 1
    - *Gunnison (CO) x 2*

Delivered in 2-7 days (average ~3-4 days)

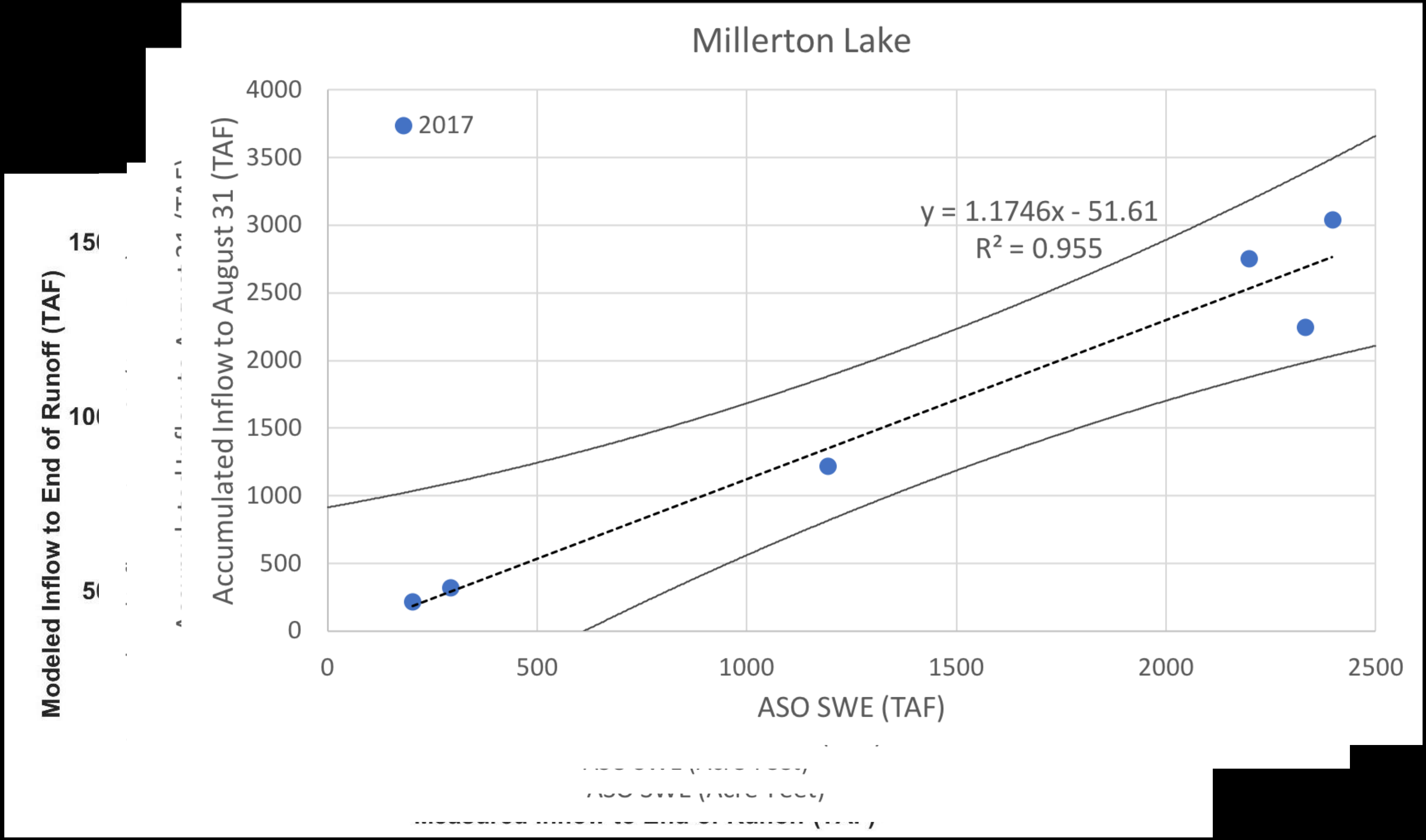
ASO 2018 season

6 years of SWE volume in the Tuolumne



Seasonal Forecasting

- à la Chris Graham plot
- Promising approach across multiple basins




Airborne Snow Observatory
ΛS